Polarimetric Passive Remote Sensing Of Wind-generated Sea Surfaces And Ocean Wind Vectors

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Abstract - **This paper investigates the theory of polarimetric passive remote sensing of wind-generated sea surfaces. A two-scale polarimetric scattering and emission model of sea surfaces is developed to interpret existing active and passive remote sensing microwave signatures of sea surfaces, and to investigate the potential application of polarimetric radiometry to ocean surface winds. Theoretical backscattering coefficients are compared with SASS geophysical model function, the accuracy of which has been confirmed by NUSCAT data, to verify the accuracy of the two-scale model, Furthermore, it is found that model-predicted azimuthal modulations of Stokes parameters of thermal radiation agree reasonably well with existing Ku-, K-, and Ka-band radiometer data. The results indicate that the azimuthal modulations observed in the microwave backscatter as well as emission data could be responsible by the same anisotropic directional surface features caused by wind forcing. Finally, we discuss issues related to passive remote sensing of ocean surface winds.**

I. INTRODUCTION

There has been an increasing interest in the microwave passive polarimetry of geophysical media [I]. Theoretical calculations for the Stokes parameters of the thermal emission have been presented for one-dimensional periodic dielectric. surfaces in [2], and for olic-dimensional occall-like rough surfaces with a prescribed power-law spectrum in [3]. The theoretical predictions were verified by the measured Stokes parameters of thermal emission from periodic soil surfaces at X band [4], and measurements over water surfaces impressed with a fiberglass layer with a sinusoidal profile at Ku band [5] and at X band [6]. All the results show that the Stokes parameters are functions of the azimuth angle between the observation direction and the corrugation direction of surfaces. however, further analysis and experiments arc necessary for two-dimensional rough surfaces.

Recently, it has been shown by Etkin et al. [7] and Wentz [8] that the brightness temperatures of horizontal and vertical polarizations, T_h and T_v, of ocean surfaces vary as functions of azimuth angles. Etkin et al. found the azimuthal dependence of brightness temperatures using their aircraft and ship-based radiometers for grazing angle (θ = 78°) observations with λ = 1.5 cm and nadir viewing with λ = 0.8, 1.5, and 8 cm. It was observed that the directional dependence rapidly dropped with increasing electromagnetic wavelength. However, the measurements were not made for the middle range of incidence angles, which is important, for spaceborne applications when spatial coverage and resolution need to be considered together. In the results published by Wentz [8], the data investigated were collected by the Special Sensor Microwave/Imager (SSM/I). After being co-registered with the buoy-measured wind vector, T_h and T_v at both 19 and 37 GHz were found to depend on wind direction. The results indicate that the directional feature of water surfaces contributes to the azimuthal variation of brightness temperatures.

Besides the above reported observations for T_h and T_v, Dzura, Etkin, Khrupin, Pospelov, and Raev [9] presented the first experimental evidence of the azimuthal variations of polarimetric brightness temperatures of sea surfaces, though the measurements were made at normal incidence and only one case was presented. Figure 5 in their paper showed that when the second Stokes parameter reached maximum, the third Stokes parameter was nearly zero, and vice versa. No explanation was provided in their paper for this observed signatures, whereas in this paper we show that the observed azimuthal variations of the second and third Stokes parameters can be explained by a two-scale surface emission model. However, since only one example was reported, and since the results were collected at nadir observation angles, more extensive experiments and analyses of the azimuthal variations of Stokes parameters over wind speeds and incidence angles are required to evaluate the applicability of polarimetric radiometry to ocean surface winds.

In view of the recent developments, a theoretical analysis based on a two-scale surface scattering and emission model for sea surfaces is presented in this paper. A two-scale sea surface model has been developed previously to derive the sea surface emission at microwaves by Wu and Fung [1 O] and Wentz [11] for isotropic random rough surfaces. However, their theory predicted no azimuthal dependence of brightness temperatures because the surface spectrum was assumed to be isotropic, and consequently, the third and fourth Stokes parameters are expected to be zero from their theory, unlike the results presented in this paper where the theory has been generalized to random surfaces with anisotropic wavenumber spectra.

In Section II, the theory of polarimetric radiometry

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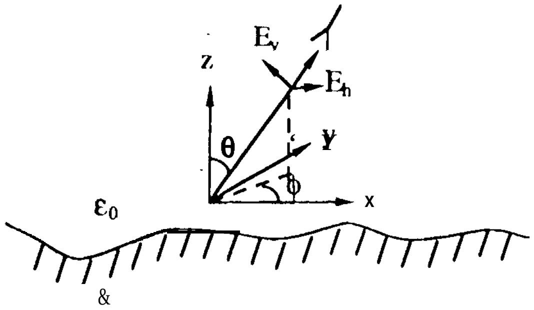

Figure 1. Configuration

is summarized. Section 111 verifies the accuracy of the scco]lc]-order small perturbation method (SPM) used in the two-scale model for rough surfaces with anisotropic directional spectra with tile Monte Carlo simulation technique for the polarimetric emission from one-dimensional random rough surfaces characterized by a power law spectrum. Section IV presents a two-scale model based on the second-order SPM for thermal emission from wind-generated sea surfaces described by an empirical wavenumber spectrum, and compares theoretical results with existing microwave backscattering coefficients and brightness temperatures of sea surfaces. Section V summarizes the results of this paper and discusses the remaining issues regarding the application of polarimetric radiometry for ocean wind vector retrieval,

11. POLARIMETRIC RADIOMETRY

For microwave polarimetric radiometry, thermal emission is described by a Stokes vector I_s with four parameters, T_h, T_v, U, and V,

$$I_s = \begin{bmatrix} T_h \\ T_v \\ U \\ V \end{bmatrix} = c' \begin{bmatrix} < E_h E_h^* > \\ < E_v E_v^* > \\ 2Re < E_v E_h^* > \\ 2Im < E_v E_h^* > \end{bmatrix} \quad (1)$$

where T_h and T_v arc the brightness temperatures for horizontal and vertical polarizations, while U and V characterize the correlation between these two polarizations. The second equality relates the Stokes parameters to the horizontally and vertically polarized components of electric fields (E_h and E_v) illustrated in Fig. 1.

By a straightforward extension of the Kirchhoff's law derived by Peake [12], the Stokes vector can be expressed in terms of the polarimetric bistatic scattering coefficients: The Stokes vector of the thermal emission from the surface plus all the reflected downwelling unpolarized radiation should be unpolarized and has the same specific intensity, when the surface is in thermal equilibrium with the surroundings. Consequently, the Stokes vector of the thermal emission from the surface with the surface temperature T_s is,

$$I_s = T_s \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} - I_r \quad (2)$$

where the first vector on the right hand side of equation is the Stokes vector for an unpolarized radiation and I_r corresponds to the total reflected radiation by the surfaces for the downwelling radiation. in terms of the polarimetric bistatic scattering coefficients $\gamma_{\alpha\beta\mu\nu}$ integrated over all the incident angles in the upper hemisphere, I_r can be expressed as

$$I_r = \int_0^{\pi/2} \sin\theta_i d\theta_i \int_0^{2\pi} d\phi_i \frac{\cos\theta_i}{4\pi\cos\theta} \begin{bmatrix} \gamma_{hhhh}(\theta,\phi;\theta_i,\phi_i) + \gamma_{hvhv}(\theta,\phi;\theta_i,\phi_i) \\ \gamma_{vvvv}(\theta,\phi;\theta_i,\phi_i) + \gamma_{vhvh}(\theta,\phi;\theta_i,\phi_i) \\ 2Re(\gamma_{vhhh}(\theta,\phi;\theta_i,\phi_i) + \gamma_{vvhv}(\theta,\phi;\theta_i,\phi_i)) \\ 2Im(\gamma_{vhhh}(\theta,\phi;\theta_i,\phi_i) + \gamma_{vvhv}(\theta,\phi;\theta_i,\phi_i)) \end{bmatrix} \quad (3)$$

Here, θ and ϕ signify the zenith and azimuth angles of the observation direction.

111. SPM FOR ANISOTROPIC ROUGH SURFACES

This section verifies the accuracy of the Stokes vector derived using the seconcl-order SPM for surfaces with anisotropic directional spectra. **As the SPM is** applied **to** random rough surfaces, the scattered field can be decomposed into coherent and incoherent components. Readers are referred to [13] for detailed mathematical expressions of the coherent and incoherent bistatic scattering coefficients. The surface emissivities (or reflectivities) calculated using the SPM are then compared with those obtained from a numerical Monte Carlo simulation technique for one-dimensional random rough surfaces with a power-law spectrum,

in simulating the random rough surfaces in the Monte Carlo simulation technique, the surface spectral density function is assumed as follows:

$$W(k_x, k_y) = q \sum_{n=1}^{10} k_x^{-3} \delta(k_x - nk_l)\delta(k_y) \quad (4)$$

where δ is the delta-function, and $k_l = 2\pi/5\lambda$ is the low-wavenumber cutoff, Here λ is the electromagnetic wavelength. Independent random numbers with the Gaussian distribution arc generated for the real and imaginary parts of each Fourier component of the surfaces, and arc further weighted by the desired spectral density. The simulated Fourier spectra are then transformed to the spatial domain by the FFT. Ten surfaces arc generated, and the factor 'q' is adjusted for the desired rms surface height (σ). The surfaces simulated by this approach arc periodic with the period corresponding to the low-wavenumber cutoff. '1'0 solve the scattering coefficients of all the reflected Floquet modes for both horizontally and vertically polarized incident waves, the Method of Moment with triangular basis for surface tangential fields and pulse weighting is used. Once the scattering coefficients arc obtained, the Stokes vectors for the emission from the simulated random surfaces arc calculated according to the Kirchhoff's law. Finally, the average of the Stokes vectors of these ten realizations is taken to represent the Stokes vector of the random surfaces.

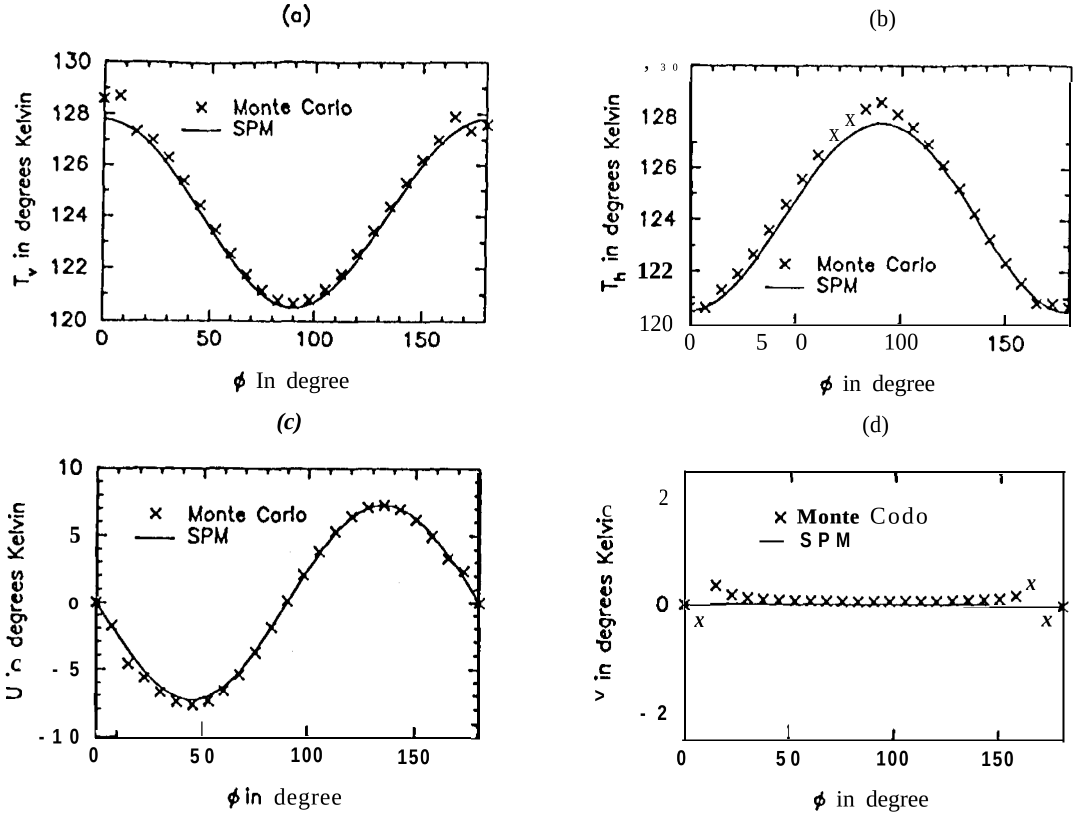

Figure 2. Comparison of the polarimetric Stokes vectors versus the azimuth angle ϕ calculated by using Monte Carlo simulation and the SPM for one-dimensional periodic random rough surfaces with $\sigma = \lambda/15$ (or $k_0\sigma = 0.419$) for $\theta = O$. The surface permittivity is 45 + 230, and a surface temperature of $T_0 = 300$ degrees Kelvin is assumed.

Figure 2 illustrates the Stokes parameters as a function of the azimuth angle ϕ for nadir viewing (θ = O degrees). The rms surface height is $\lambda/15$, which can be translated into $k_0\sigma$ = 0,419. The dielectric constant of 45 + $i30$ is assumed for the surfaces. The results calculated by using the SPM arc in close agreement with those obtained from the Monte Carlo simulation. Additionally, it is found that the Stokes parameters have a cos 2ϕ variation in azimuth for T_h and T_v, sin 2ϕ for U, and zero for V, which are expected for nadir viewing.

Similar comparison has also been performed for incidence angles up to 60 degrees. Excellent agreement is seen between the SPM and the Monte Carlo simulation with the difference in general less than 0.2 degree K.

IV. TWO-SCALE SURFACE MODEL AND COMPARISON WITH ACTIVE AND PASSIVE REMOTE SENSING DATA

To develop the two-scale model for sea surface scattering and emission, we follow the approach taken by Wu and Fung [1 o], averaging the scattering and emission coefficients I_s of small-scale surfaces over the slope distributions of large-scale surfaces:

$$\bar{I}_s = \int_{-\infty}^{\infty} dS_y' \int_{-\infty}^{\cot\theta} dS_x' I_s (1 - S_x' \tan\theta) P(S_x, S_y) \quad (5)$$

where

$$\begin{aligned} S_x' &= S_x \cos\phi + S_y \sin\phi \\ S_y' &= -S_x \sin\phi + S_y \cos\phi \end{aligned} \quad (6)$$

In the above expressions, $P(S_x, S_y)$ denotes the slope distribution function of large-scale surfaces with S_x and S_y representing the surface slopes in x (up-wind) and y (cross-wind) directions. The slope distribution function $P(S_x, S_y)$ is assumed to be Gaussian with the up and cross-wind slope variances calculated from all surface spectrum components with wavenumber numbers less than a selected two-scale cutoff k_d. Note that the integration over S_x' is limited to cot θ to account for the effects of shadowing clue to other large-scale surfaces. Finally, the Stokes vector of thermal emission from the two-scale surfaces is represented by $\bar{I}_s$.

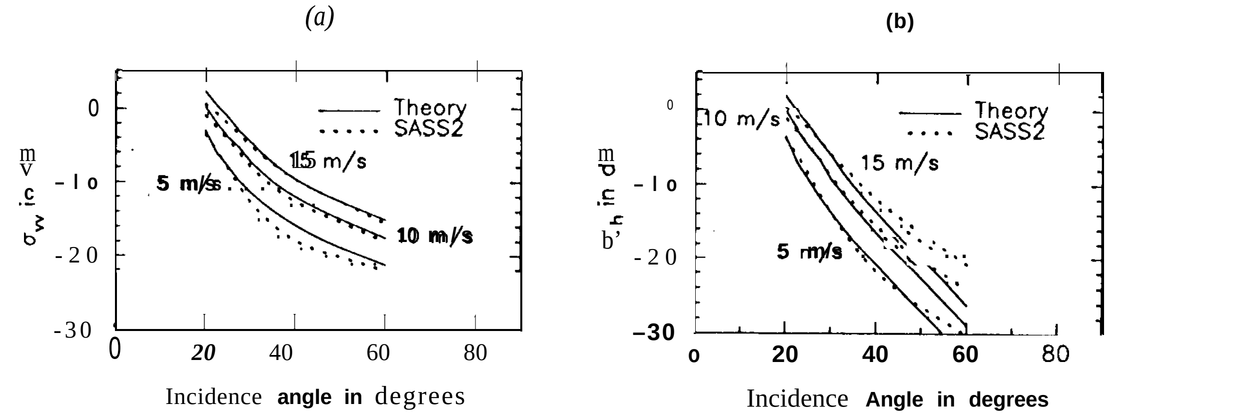

Figure 3. Comparison of theoretical backscattering coefficients of sea surfaces in the up-wind direction with SASS geophysical model function [15] as functions of incidence angles. A surface temperature of $T_s = 10$ degrees Celsius is assumed.

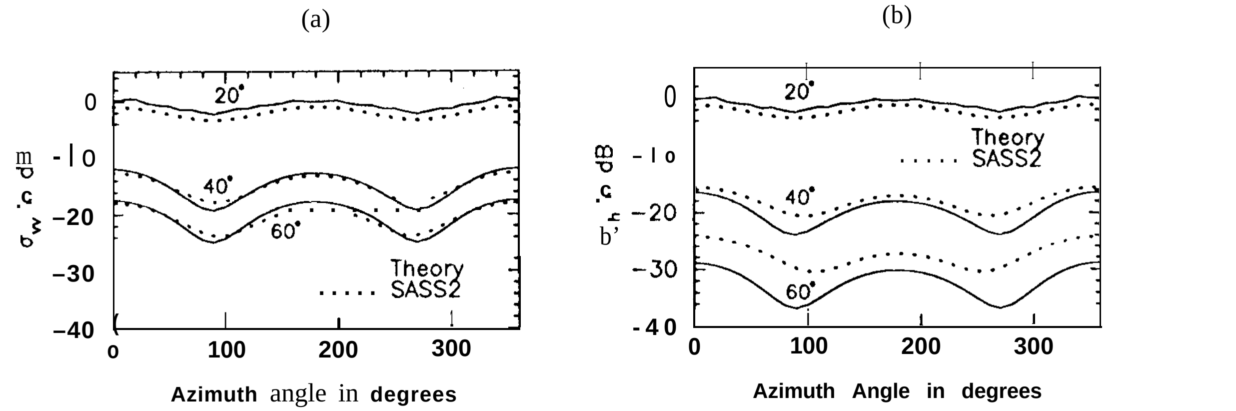

Figure 4. Comparison of theoretical backscattering coefficients of sea surfaces with SASS geophysical model function [15] as functions of azimuth angles for the wind speed of 10 m/s. Curves for three incidence angles 20, 40, and 60 degrees are illustrated. A surface temperature of $T_s = 10$ degrees Celsius is assumed.

Likewise, the backscattering coefficients from the two-scale surface model are calculated using the same formulation but with I_s replaced by the backscattering coefficients of small l-scale surfaces inside the integral.

In the following, theoretical backscattering coefficients and polarimetric brightness temperatures are compared with existing active and passive remote sensing measurements of sea surface microwave signatures.

The wind-induced surfaces are described by an empirical surface spectrum proposed by Durden and Vesecky [14]. (Due to some typographical errors found in their paper, the correct expressions of these formulas can be found in [13].) We let the spectrum of small-scale surfaces be the same as that of the complete spectrum for the wavenumbers above a certain cutoff k_d, and set to be zero, otherwise. The values of roughness parameter $k_0\sigma$ for two wavenumber cutoffs ($k_d = 60$ and 80) at 14 GHz (Ku band) have been evaluated for wind speeds up to 20 m/s with the spectral parameter $a_0 = 0.006$, which is 1.5 times of that used by Durden and Vesecky [14], and are all less than 0.42. Hence, we should expect the SPM to be applicable to these cases according to the results shown in the previous section.

Figs. 3 and 4 compare theoretical Ku-band backscatters with SASS geophysical model function [15] for the up-wind backscatter vs. incidence angle and the azimuthal backscatter modulations with $a_0 = 0.006$. Reasonable agreements are seen between theory and data for the absolute magnitudes of backscattering coefficients, except for the cases of large incidence angles. The discrepancy at large incidence angles, in particular backscatter for horizontal polarization, is known to be possibly caused by breaking waves which have not yet been considered. Nevertheless, the magnitudes of theoretical azimuthal modulation remain fairly similar to data.

Fig 5 compares the aircraft radiometer measurements [9] with the theoretical results plotted as functions of tile azimuth angle for nadir viewing at $f = 14$ GHz with $k_d = 80$. Theoretical calculations for $k_d = 60$ have also been carried out, and results differ from those for $k_d = 80$ by less than 0.1 degree K. The measurement data were read from Figure 5 in [9] and represent the average through the curves at each azimuth angle with an expected

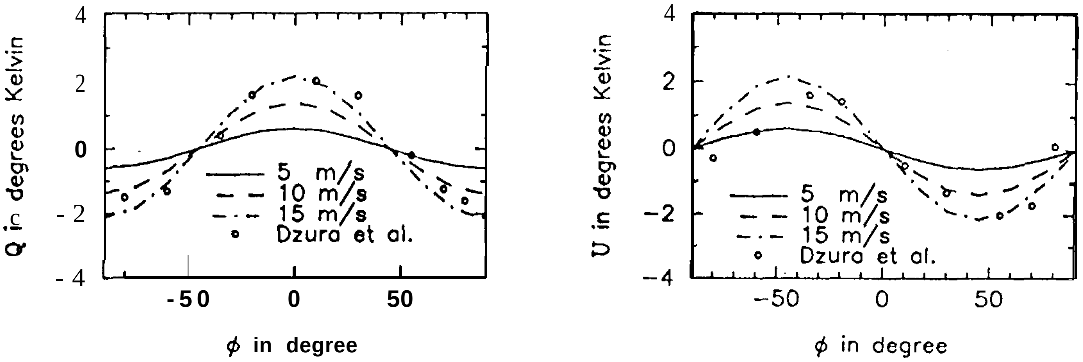

Figure 5. Comparison of theoretical Stokes parameters of of sea surfaces with the aircraft Ku-band radiometer data reported in [9] as functions of azimuth angles, A surface temperature of $T_s = 10$ degrees Celsius is assumed. Theoretical data for three wind speeds are illustrated, and the reported wind speed in [9] is 10 m/s.

uncertainty of ± 0.5 degrees. It can be seen that the directional features of theoretical Stokes parameters Q = $(T_v - T_h)$ and U are just like those of one-dimensional surfaces presented in the previous section, and the magnitudes of azimuthal variations increase as the wind speed increases.

in addition, the directional dependence of Stokes parameters Q and U agree fairly well with the aircraft radiometer measurements, though the theoretical results for 10 m/s wind speed, which was the wind speed reported in [9], underpredict the magnitude of azimuthal variations. This discrepancy could be caused by the difference between the assumed and true sea surface spectrum, or the sea surface features (such as, foams) which are not considered in this paper.

Figs. 6(a) and (b) compare theoretical up- and crosswind brightness temperature difference with measurements collected by Etkin et al. [7] and SSM/I model function [8]. In general, the agreement can be considered rather well, though it seems that the theory incorrectly predicts the incidence angle where the wind speed sensitivity of vertical polarization crosses zero when compared with SSM/I data. Figs. 6(c) and (d) illustrate theoretical U and V for a fixed azimuth angle of 45 degrees between up- and cross-wind directions as a function of incidence angle. Values of U are a few degrees Kelvin, while V is in general small except at large incidence angles.

V. SUMMARY

In this paper, **a two-scale sea surface scattering and** emission model **is** presented **to analyze the** polarimetric emission from two-dimensional random rough surfaces with an anisotropic directional spectrum. The accuracy of the SPM used in the two-scale model was quantified by the Monte Carlo simulation technique for the emission from one-dimensional rough surfaces with a power law spectrum. Theoretical backscattering coefficients and brightness temperatures are shown to agree reasonably well with the azimuthal modulations observed in SASS geophysical model function [15] and sea surface brightness temperatures presented in [7, 8, 9].

The aircraft- and ship-based radiometer data [7, 9] and SSM/I model function [8] together with the results of this paper indicate that the passive radiometry is a potential technique for the remote sensing of ocean wind vector. However, several issues not addressed in this paper need further investigation by either more extended theoretical analyses or measurements to determine the model function of Stokes parameters. in this regard, experiments should be carried out for sea surface emission at a large range of observation angles θ from O up to 70 degrees, which are important for spaceborne remote sensing applications. Moreover, the sensitivity of wind speed and direction versus the microwave frequency should be determined to allow the selection of optimal frequency bands for the radiometer measurements of ocean wind fields. Finally, the design of passive radiometers which are capable of measuring at least the first three Stokes parameters with the required accuracy and stability of a few tenths of a degree Kelvin should be studied.

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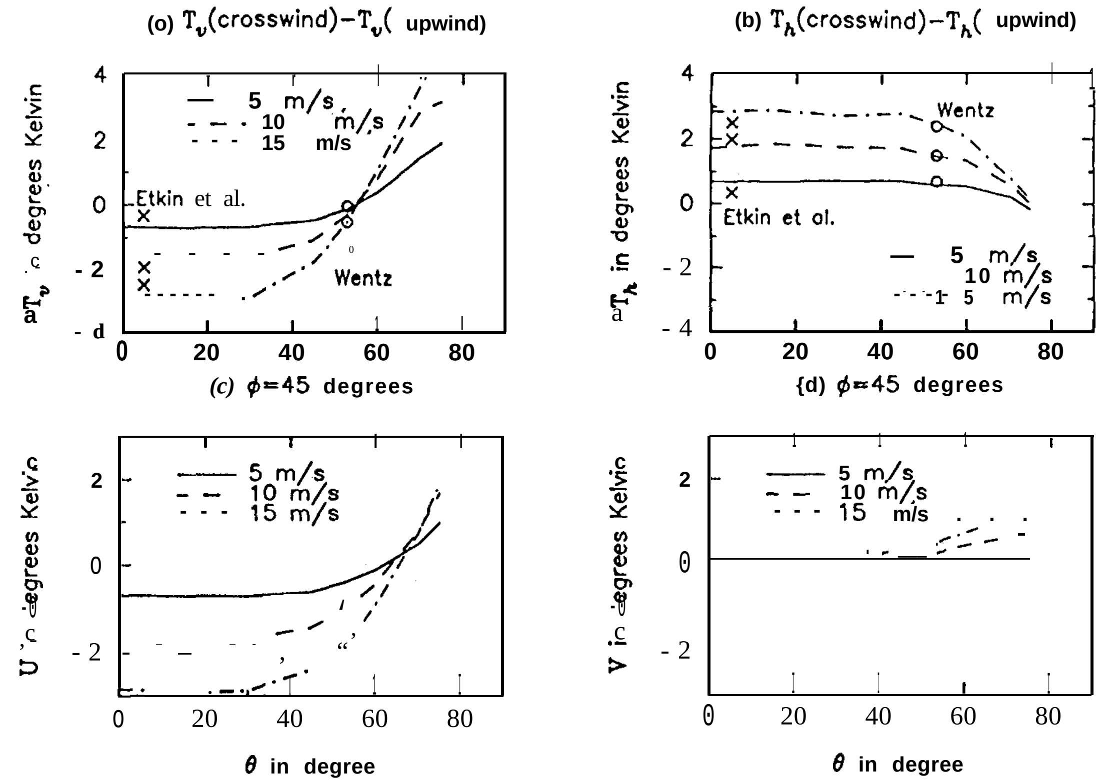

Figure 6. Comparison of anisotropic azimuthal variations of theoretical Stokes parameters of of sea surfaces with the aircraft Ka-band radiometer data reported in [9] and SSM/I as functions of azimuth angles. A surface temperature of $T_s = 10$ degrees Celsius is assumed. Data and theory for three wind speeds arc illustrated, No measurements for *U* and V have yet been reported.

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